

Spin Bias Measurement Based on a Quantum Point Contact

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Abstract

Electron charge transport through a quantum point contact (QPC) driven by an asymmetric spin bias (SB) is studied. A large charge current is induced when the transmission coefficient of the QPC jumps from one integer plateau to the next. Furthermore, for an open external circuit, the induced charge bias instead of the charge current is found to be quite large. It provides an efficient and practical way to detect SB by using a very simple device, a QPC or a STM tip. In addition, with the aid of magnetic field, polarization direction of the SB can also be determined.

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The field of spintronics has received more and more attention recently. The spin current is one of the most important physical quantities in spintronics,[1, 2] similar to the role of the charge current played in electronics. Important issues of spintronics include how to generate, manipulate, and detect the spin current. Various methods have been proposed to generate spin current.[3, 4, 5, 6, 7, 8] Up to now, the spin current has been generated by various means, e.g., the pump excitation,[4] the optical injection,[5] the magnetic injection[6, 7], and the spin Hall effect.[8] To measure the spin current, the light-emitting diode or Kerr-rotation spectroscopy has been experimentally used to detect the spin-current induced spin accumulation near the boundaries of the sample.[8] Moreover, an electric measurement was also realized via the inverse spin Hall effect.[7] In addition, theoretical proposals on indirect measurement of spin current were also available.[9, 10, 11, 12] These include the detection of the spin torque caused by a spin current flowing through a ferromagnetic-nonmagnetic interface[9] and the detection of the spin-current induced electric field.[10, 11] However, all these experimental instruments are delicate and complicated. They always involve the optical and magnetic factors, or spin-orbit interaction. Up to now, there is yet a practical and effective approach to measure spin current. Hence the measurement of the spin current remains a challenge.

In charge transport, one can measure the charge bias instead of the charge current. For a spin current flowing through a device, a spin-dependent chemical potentials (spin bias, SB) is usually induced that is the driving force of the spin current. We can measure this SB instead of spin current. In this paper, we propose an effective method to detect the SB by using a quantum point contact (QPC) or a STM tip. The QPC is the simplest device in mesoscopic physics. The transport property of the QPC has been investigated extensively. Its conductance versus the gate voltage V_g shows a series of step structures at the value $2ne^2/\hbar$ ($n = 1, 2, \dots$). Experimentally, the QPC has been used as a charge sensing detector to reliably probe the number of electrons in the quantum dot.[13] Our results show that a charge bias or charge current emerges when the QPC is biased by an asymmetric SB.[14] Therefore by measuring the induced charge bias, we can detect the SB in a very simple way.

The proposed device is a QPC device under an asymmetric SB as shown in Fig.1a.[15] Our task is to “experimentally” measure the SB. A concrete example of the device is shown in Fig.1c that is based on the experimental setup used in Ref.[7] where a ferromagnetic (FM) lead crossed over an aluminium (Al) lead. A charge current is injected from the FM lead

into one terminal of Al lead, then a pure spin current is generated and flows into another terminal of the Al lead. A spin-dependent chemical potentials (i.e. SB) is created there.[7] Of course, the SB can also be generated using other methods. In this paper, we propose to measure this SB by using a STM tip (see Fig.1c) or a QPC device.

Let us first discuss the working principle of detecting the SB using the QPC. Due to the asymmetric SB V_s , [14] the chemical potentials on the left lead are spin-dependent with $\mu_{L\uparrow} = E_f + V_s$ and $\mu_{L\downarrow} = E_f - V_s$, but the chemical potentials on the right lead are still spin independent with $\mu_{R\uparrow} = \mu_{R\downarrow} = E_f$ (see Fig.1a). Under the SB V_s , the charge current I_σ (with $\sigma = \uparrow, \downarrow$) is given by the Landauer-Büttiker formula:

$$I_\sigma = \frac{e}{h} \int dE T(E) [f_{L\sigma}(E) - f_{R\sigma}(E)] \quad (1)$$

where $T(E)$ is the transmission coefficient and $f_{p\sigma} = 1/\{\exp[(E - \mu_{p\sigma})/k_B T] + 1\}$ is the Fermi distribution of the leads. From Eq.(1), the spin-up and spin-down currents, I_σ with $\sigma = \uparrow, \downarrow$ or $\sigma = \pm$ are mainly determined by $T(E)$ with E between $\mu_{R\sigma} = E_f$ and $\mu_{L\sigma} = E_f + \sigma V_s$. Note that the transmission coefficient $T(E)$ is energy dependent. In particular, when the energy E is at the middle of the jump as shown in Fig.1b, $T(E)$ is strongly dependent on E . In general, $|I_\uparrow|$ is not equal to $|I_\downarrow|$. As a result, a net charge current $I_c = I_\uparrow + I_\downarrow$ occurs although I_\uparrow and I_\downarrow flow in opposite directions. So by measuring the induced charge current I_c , we can detect the SB V_s . In the following, we shall investigate I_c as well as the relation between I_c and V_s in detail.

To calculate I_c , we assume the QPC device is described by the Hamiltonian $H = (p_x^2 + p_y^2)/2m^* + V(x, y)$. In the QPC region ($|x| \leq L/2$ and $|y| \leq W/2$), the potential is assumed in a saddle form $V(x, y) = \beta \frac{y^2}{W^2} - \frac{V_g}{\cosh^2(\alpha x/L)^2}$. In the lead regions ($|x| > L/2$ and $|y| \leq W_{lead}/2$), $V(x, y) = 0$. $V(x, y) = \infty$ outside of lead and QPC regions. In the tight-binding representation, the Hamiltonian becomes:[16] $H = -t \sum_{\langle \mathbf{i}, \mathbf{j} \rangle, \sigma} a_{\mathbf{i}\sigma}^\dagger a_{\mathbf{j}\sigma} + \sum_{\mathbf{i}, \sigma} (4t + V_{\mathbf{i}}) a_{\mathbf{i}\sigma}^\dagger a_{\mathbf{i}\sigma}$, where $\mathbf{i} = (i_x, i_y)$ labels the site index, $t = \hbar^2/2m^*a^2$ is the nearest neighbor hopping matrix element, a is the distance between two neighboring sites, and $V_{\mathbf{i}} = V(i_x a, i_y a)$. From the discretized Hamiltonian H , the transmission coefficient $T(E)$ is given by $T(E) = \text{Tr}[\mathbf{\Gamma}_L \mathbf{G}^r \mathbf{\Gamma}_R \mathbf{G}^a]$ where we have used the Green function $\mathbf{G}^r(E) = [\mathbf{G}^a]^\dagger = \{E\mathbf{I} - \mathbf{H}_0 - \sum_p \mathbf{\Sigma}_p^r\}^{-1}$ and the line-width function $\mathbf{\Gamma}_p = i(\mathbf{\Sigma}_p^r - \mathbf{\Sigma}_p^{r\dagger})$. Here \mathbf{H}_0 is the Hamiltonian of the QPC's region and $\mathbf{\Sigma}_p^r$ is the retarded self-energy due to the coupling between the lead p and the QPC. With $T(E)$, the charge current can be calculated from Eq.(1).

In the numerical calculation, we set the hopping strength $t = 1$ as the energy unit. The width of the leads is set to $W_{lead} = 500a$, and the QPC sizes are chosen as $W = 50a$ and $L = 100a$. The parameters α, β of the QPC's saddle potential are $\alpha = 5$ and $\beta = 4t$. The Fermi energy E_f is fixed at $0.6t$ that is near the band bottom 0. Fig.2(a) and (b) show the charge current I_c versus the gate voltage V_g at different SB V_s and at different temperatures \mathcal{T} , respectively. For comparison, the transmission coefficient $T(E)$ at $E = E_f$ versus V_g is also plotted in Fig.2(b) (see gray solid line) which exhibits a series of step structures. For parameters we used, the curve of $T(E_f)-V_g$ is very similar to the curve of $T(E)-E$ at fixed V_g (not shown here). In the system, the charge current I_c indeed is nonzero for nonzero SB V_s . From Fig.2 we see that I_c-V_g curves exhibit a series of peaks with approximately the same peak height. In addition these peaks are well correlated with dT/dV_g . For instance, I_c reaches the maximum value whenever the transmission coefficient T shows a jump. With increasing of V_s , the current I_c increases as a whole (see Fig.2a). When increasing the temperature \mathcal{T} from zero, I_c near the peak decreases while I_c near the valley increases. As a result, the curve of I_c versus V_g is smoothed out by temperature effect.

Experimentally, it is more convenient to measure the voltage. In the following, we consider an open external circuit where a charge bias V_c is induced instead of the charge current I_c passing through. Due to the induced charge bias V_c , the chemical potential $\mu_{R\sigma}$ of the right lead is shifted from E_f to $E_f + V_c$. With condition $I_c = 0$ in the open circuit, V_c can be determined through Eq.(1). In Fig.3a and b, the ratio V_c/V_s are plotted with the same parameters used in Fig2a and b. We see V_c/V_s has similar characteristics as I_c : V_c/V_s exhibits a series of peaks, increases with increasing V_s , and it is also smoothed out by the temperature effect. However, there are two big differences between I_c and V_c . First, the peak heights of V_c/V_s decrease as $|V_g|$ decreases, while they are nearly same for I_c . Second, on the left side of the first peak (at $V_g \approx -0.56$), I_c is very small but V_c/V_s is always quite large.

Fig.3c shows the ratio V_c/V_s versus V_s at different gate voltages V_g . When V_s increases from the zero, V_c/V_s rises quickly and then saturates eventually. We emphasize that the ratio V_c/V_s is very sensitive to V_s at small V_s . For instance V_c/V_s is larger than 0.1 at $V_s = 0.002t$. Fig.3d gives the effect of temperature on the bias ratio V_c/V_s . We see that the peak of V_c/V_s decreases while the valley of V_c/V_s increases with the temperature. In the high temperature limit, V_c/V_s converge to a constant value for all V_s . Notice that the high temperature limit

of V_c/V_s is quite large (≈ 0.1). This means that the SB V_s can be measured even at high temperatures.

Let us discuss the feasibility of our proposal. First, the induced charge bias V_c is quite large. V_c/V_s can be over 0.5 at the certain region (e.g. while $V_g < -0.57$ as shown in Fig.3). In particular, V_c/V_s is larger than 0.01 for almost all regions of the parameter including the SB V_s , the gate voltage V_g , the temperature \mathcal{T} , etc. In the present technology, the charge bias of order of $0.1nV$ can easily be measured.[17] Therefore, our QPC device can detect V_s if it is over $10nV$. In fact, in the Ref.[7] the SB V_s has been estimated to be on the order of $10\mu V$ which is three order of magnitude larger than $10nV$.

So far we have discussed how to detect the magnitude of the SB. However, the SB is a vector with its magnitude and spin polarized direction.[18] Its polarized direction can be determined in the following way. We apply a magnetic field \mathbf{B} to the QPC. Due to the Zeeman effect the transmission coefficient $T_\sigma(E)$ becomes spin-dependent. Note that $T_\uparrow(E)$ is increased and $T_\downarrow(E)$ is decreased when \mathbf{B} is nonzero, where $\sigma = \uparrow, \downarrow$ represent the parallel and antiparallel direction of \mathbf{B} , respectively. As a result, the induced charge current I_c or charge bias V_c is also affected. By varying the direction of magnetic field \mathbf{B} , I_c or V_c reaches maximum value when the direction of \mathbf{B} is parallel to the spin polarized direction of the SB V_s . Therefore the direction of V_s can be determined.

In summary, when an asymmetric spin bias (SB) is applied on a quantum point contact device or a STM tip, a charge current or charge bias is induced. The SB can be determined by measuring the induced charge current or charge bias. Our analysis shows that the induced charge bias is quite large for almost all parameters and is well within the reach of the present technology. Hence our proposed device can efficiently measure the magnitude of the SB by an electrical measurement. In addition, the spin polarization direction of the SB can also be measured in the presence of magnetic field.

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FIG. 1: (Color online) (a) Schematic plot of an asymmetric SB applying on a QPC. (b) The transmission coefficient $T(E)$ vs the energy E for a typical QPC device. In (a) and (b), the spin-dependent chemical potentials $\mu_{L\sigma}$ are also shown. (c) Schematics of a suggested device is shown where a FM lead crossed over an Al lead. A spin current is injected into the Al lead and a SB is generated along the Al lead. A tip of STM as a detector to detect the SB.

FIG. 2: (Color online) (a) I_c vs V_g at zero temperature \mathcal{T} for $V_s = 0.005$ (solid line), 0.01 (dashed line), and 0.02 (dotted line). (b) I_c vs V_g at fixed $V_s = 0.02$ for $k_B\mathcal{T} = 0$ (solid line), 0.005 (dashed line), and 0.01 (dotted line). For comparison, $T(E_f)$ vs V_g is also plotted in (b), [see gray (or red) solid line].

FIG. 3: (Color online) (a) and (b) are V_c/V_s vs V_g for different SB V_s (a) and different temperature $k_B\mathcal{T}$ (b). (c) is V_c/V_s vs V_s for different V_g , and (d) is V_c/V_s vs \mathcal{T} for different V_g . The other parameters are same to that in Fig.2.





